Interdisciplinary Modeling and Dynamics of Archipelago Straits

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LONG-TERM GOALS

The general focus of this work is to explore, better understand, model and predict the interactive dynamics and variability of sub-mesoscale and mesoscale features and processes in the Philippine Straits region and their impacts on local ecosystems through
  i.   physical-biogeochemical-acoustical data assimilation of novel multidisciplinary observations,
  ii. adaptive, multi-scale physical and biogeochemical modeling,
 iii. process, sensitivity studies based on a hierarchy of simplified simulations and focused modeling.

OBJECTIVES

 - Utilize and develop the Error Subspace Statistical Estimation (ESSE) system for interdisciplinary data assimilation and uncertainty estimation with the physical Primitive-Equation (PE) and generalized biogeochemical model of the Multidisciplinary Simulation, Estimation, and Assimilation Systems (MSEAS) group
 - Study, describe and model the variability and dynamics of flow separations and associated eddies and filaments, of water mass evolutions and pathways, and of locally trapped waves
 - Develop and implement schemes for parameter estimation and selection of model structures and parameterizations, and for high-resolution nested domains towards non-hydrostatic modeling

APPROACH

The technical approach is based on ocean dynamical modeling with free-surface primitive equation models with tidal forcing. It involves interdisciplinary data assimilation with ESSE, quantitative model evaluation and selection through adaptive modeling, and sensitivity and dynamical process studies. The ongoing physical and biogeochemical applications and scientific research focus on:
• Physical and interdisciplinary data assimilation (DA) of novel multidisciplinary data types
   ○ measurement models and interdisciplinary DA: investigate multi-grid DA/ESSE combination
   ○ high-resolution DA: assimilate sub-inertial processes and interactions without aliasing
• Process and sensitivity studies
   ○ processes: variability and dynamics of flow; pathways and transformation of water masses; tidal – buoyancy flow interactions; biological responses; blooms; biological accumulations
   ○ model-based studies: sensitivity studies; term and flux balances and transports; energy diagnostics; estimation of dominant scales of variability; predictability

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- Adaptive physical and biogeochemical modeling including: adaptive modeling, tidal modeling and multi-dynamics nested domains and non-hydrostatic modeling

WORK COMPLETED

Realistic Multiscale Simulations, Real-time Forecasts and Dynamics
PHILEX – IOP09: The nearly two-month long Intensive Observation Period for PHILEX required significant effort both prior to and during the IOP. In preparation for the exercise, various model parameters (bottom friction, mixing, etc.) were tuned, various pieces of software (biology, masking, objective analyses, two-way nesting, data assimilation) were debugged, generalized inverse barotropic tidal fields were prepared, appropriate historical synoptic and climatological data were acquired, etc. During the exercise, real-time forecasts of physical and biological fields were generated at three to four day intervals; synoptic data and remotely sensed products (SST, SSC, SSH) were acquired, processed and made available; and summaries were generated for web dissemination. Re-analyses were carried out in real-time, for both the physics and the biologics, at various resolutions in the Archipelago and Strait domains. Some illustrations are provided here (see Figs. 1-3). All real-time and re-analysis products are available from http://mseas.mit.edu/Sea_exercises/Straits/index.html.
One of the novel aspects of this forecasting exercise was our total dependency on remote data to initialize and maintain the synoptic features.   SSH anomaly images were mapped onto our modeling domain. From these anomalies, an estimate of velocity was constructed from weak geostrophic constraint and a vertical extension using a Gaussian decay scale of 500m. The surface elevations and velocity fields were added to the geostrophic estimates obtained from climatology. For open boundary conditions (OBC), the transports from the HYCOM model were used. Our high-resolution tidal forcing was also used at the OBCs of our free-surface simulations (as well as in the initial conditions).

Coupled Physics-Biology IOP09 Forecasts and Re-analyses: The Dusenberry-Lermusiaux biological model was used. Fields for six state variables (chlorophyll, nitrate, ammonium, detritus, phytoplankton, and zooplankton) were needed to initialize simulations. Using biological parameters from literature, climatology from World Ocean Atlas data for nitrate and chlorophyll profiles extracted from satellite data, a first guess at initial fields were computed using our new region-dependent procedure. Dynamical equations were then used in a weak constraint form to estimate the other initial fields (detritus and zooplankton). The outputs are fields in quasi-dynamical equilibrium, which depend on the parameters of the equations. Hence, our choice of parameters and of initial conditions is coupled. To evaluate the skill of our real-time biological forecasts and re-analyses, chlorophyll field estimates were compared to satellite images (Figure 4).

Inverse Tidal Modeling: Tidal forecasts and descriptions were provided to support the observational and modeling work. The data from ADCP moorings deployed by Dr. Janet Sprintall and her team were utilized to tune the tidal model and obtain the inverse estimates of the OBCs.

Statistical Field Estimation for Complex Coastal Regions and Archipelagos: New schemes have been derived and utilized for the mapping of ocean fields in complex multiply-connected domains (Agarwal, 2009). Our original multi-scale OA approach consists of successive utilizations of Kalman update steps, one for each scale and for each correlation across scales. The approach has been extended to field mapping in complex, multiply-connected, coastal regions and archipelagos, with a focus on PHILEX. The main update is in the OA correlation function which requires an estimate of the distance between data and model points, without going across complex landforms. Our new codes efficiently estimate the length of the shortest sea paths using the Level Set Method (LSM) and Fast Marching

Method (FMM). They were implemented and utilized in idealized and realistic cases. These schemes were required to initialize our real-time forecasts for IOP09. Their computational properties were studied and compared to other schemes (Agarwal, 2009).

Optimizing the Inter-island Transport for Complex Coastal Regions and Archipelagos: The computation of geostrophic shear velocity is well established for open oceans, without any coastlines or islands. A novel methodology has been developed for computing the transport streamfunction along island coastlines in complex coastal regions and archipelagos by minimizing (or fitting) the inter-island transport. The scheme has been used for PHILEX. It uses the Fast Marching Method (FMM) or Level Set Method (LSM) to compute the minimum vertical area between all pairs of islands and eliminates spurious velocity hot-spots. These estimates of transport streamfunction are required for the initialization of velocity fields in ocean models based on geostrophy and temperature and salinity data.

Adaptive Estimation of scales directly and only from irregular ocean data: Agarwal (2009) developed and utilized novel methods for the adaptive estimation of spatial-temporal scales from irregular ocean data. The three novel schemes are based on the use of structure functions, short term Fourier transform and second generation wavelets. To our knowledge, this is the first time that adaptive schemes for the estimation of spatial-temporal scales are proposed. The ultimate goal of all these methods would be to create maps of spatial and temporal scales that evolve as new ocean data are fed to the scheme.

Idealized Simulations and Dynamics
Numerics for Idealized Coupled Physics-Biology Simulations with Advection Dominated Flows: The central difference, donor-cell, hybrid (central difference with donor-cell), Weighted Essentially Non-Oscillatory (WENO) and unstructured-grid Finite-Element Galerkin schemes were compared (Burton, 2009; Ueckermann, 2009) to estimate which was most appropriate for simulating idealized biological dynamics in straits. Simulations should allow a wide range of processes, including advection dominated flows, have limited costs and keep low numerical diffusion. The Arakawa C-grid and Operator Splitting Method are used. The velocity field is a potential flow. Periodic boundary conditions are used in the horizontal and Neumann conditions on the air-sea interface and bottom bathymetry. Initial biology fields are obtained from stable equilibrium values of the NPZ equations.

Global Equilibria and Local Stability of Coupled NPZ Equations: Three analytical sets of equilibria were derived for a set of NPZ equations without flow (Burton, 2009). These equilibria correspond to deep water conditions, near-surface conditions and an unfeasible (always negative) solution. Stability of the near surface equilibria was then studied in terms of depth and total biomass, identifying where to expect stable and unstable solutions based on the value of phytoplankton and zooplankton. The local stability predictions and effects of diffusion were then tested in idealized 2D simulations.

*Sensitivity of Biological Activity to Oscillatory Flow***:** Tides are a dominant physical feature in the San Bernardino Strait, with several different tidal constituents. To determine effects of tides on biological activity, we forced idealized biological simulations and completed analytical studies with a range of oscillating flow frequencies. Velocity fields were scaled to match typical flow velocities observed in the strait. Smoothed bathymetry was used. Various parameters and levels of diffusion were tested. The biological responses were studied as a function of the biological and physical time scales. Lastly, the biological activity (measured as the standard deviation over time of the total amount of each state variable along a streamline) was recorded for different oscillation frequencies and for four streamlines.

RESULTS

Realistic Multiscale Simulations, Real-time Forecasts and Dynamics
PHILEX – IOP09: The reanalysis of the real-time activity has driven a number of process and sensitivity studies which are underway. These include: biological-physical dynamics in straits (e.g. San Bernadino, Surigao, Mindoro); impact of Sulu Sea gyres on overflow effects and formation of deep Sulu Sea Water (Figs. 1-3); relative contributions of wind-driven vs. density-driven vs. tidally-driven circulations in shallow areas; and, impacts of larger-scale transports at open domain boundaries.

When adding SSH anomaly (and corresponding velocity) fields to the initial and boundary fields, density fields should be adjusted to support these velocities. We found that direct assimilation can be used to accomplish this. Specifically, re-assimilating SSH-constrained velocities with full strength, ramped over the corresponding day, displaced the isopycnals by JEBAR while maintaining the imposed velocity field. A second, related result is that DA by simply melding of the sea surface height only was insufficient to force the adjustment of isopycnals. If DA by melding is used, assimilating the corresponding extended geostrophic velocity estimate is necessary.

Coupled Physics-Biology IOP09 Forecasts and Re-analyses: Several biogeochemical dynamic studies are underway. Our biological initialization scheme was further improved. First, chlorophyll profiles were created from SSC satellite data. The domain was divided into three regions that are distinct biologically. Generic profiles were created for each, based on experimental data from Cordero, et al., 2007. Satellite data was combined over two weeks for more complete coverage. Profiles at each point were then scaled to match the integrated satellite data. The other initial fields are found using WOA climatology and by balancing the reaction terms of the biological equations and iterating. To compare forecasts to data, modeled chlorophyll fields were integrated into sea surface chlorophyll and averaged over one week (Figure 4). The field patterns matched well, with mean differences on the order of 0.1 mg/m^3, but they can be improved both by better physics and better biology.

Inverse Tidal Modeling: Tides were found to dominate ocean dynamics in the Surigao and the San Bernardino straits, with model velocities up to 150 cm/s. The spatial structure of the flow fields through the straits is highly spatially inhomogeneous (Figure 5) which makes the role of models in predicting the flow fields indispensable. Our inverse techniques also proved necessary to capture the phases of the flow fields through the straits.

Statistical Field Estimation for Complex Coastal Regions and Archipelagos: A manuscript on our new methods for OA based on estimating the length of shortest sea paths using LSM and FMM is ready to be submitted. These new schemes could improve widely-used gridded databases such as the climatological gridded fields of the World Ocean Atlas (WOA) since these oceanic maps were computed without accounting for coastline constraints. The new schemes have been compared with other approaches, including the use of stochastically forced partial differential equations (SPDE) (Figures 6 and 7). The FMM-based scheme for complex, multiply-connected, coastal regions has been found to be more efficient and accurate than the SPDE approach. Field maps computed with our FMM-based scheme do not require post-processing (smoothing) of fields. This methodology has been applied in the complex domains of Philippines Archipelago (and also Dabob Bay, see Agarwal, 2009).

Optimizing the Inter-island Transport for Complex Coastal Regions and Archipelagos: Without this scheme, velocity fields constrained by geostrophy with OA-ed hydrographic data cannot be used for initialization in very complex domains such as those of PHILEX. A note is ready to be submitted.

Adaptive Estimation of scales directly and only from irregular ocean data: This adaptive scale estimation could be a significant advance towards better understanding and sampling of ocean processes. Dominant spatial scales measured in the PHILEX region varied from 30 to 70km.

Idealized Simulations and Dynamics
Numerics for Idealized Coupled Physics-Biology Simulations with Advection Dominated Flows: Advection dominated flows are prone to spurious oscillations. For C-grids on idealized 2D (x, z) strait domains with a stair-case bathymetry, we found that the central difference and hybrid schemes produced oscillations for almost all cases. The donor-cell and WENO schemes were both non-oscillatory, but a comparison of numerical diffusion versus computational time revealed that the WENO scheme performed better for all resolution sizes (Figure 8) except for very coarse resolution, which is not sufficient for coupled physics and biology. Our new hybrid discontinuous Galerkin schemes on unstructured grids have also been used on the same problem. Comparisons are underway.

Global Equilibria and Local Stability of Coupled NPZ Equations: The global equilibria derived were closed form and functions of the biological reaction terms and their parameters. Another closed form expression was derived to determine when the transition from a stable to unstable regime (or vice versa) occurs, in terms of system parameters and depth. A local stability analysis (based on eigenvalues of the local Jacobian) characterized the linear sensitivity, which was verified using phase portraits in the phytoplankton-zooplankton space. Results from the idealized simulation (now adding flow and diffusion) revealed that advection stabilized cases with very small positive eigenvalues (which were thus classified as unstable in the local stability analysis) and adding diffusion stabilized an even wider range of cases. Therefore, the stability analysis in the domain without advection or diffusion is for the NPZ domain used a conservative estimate for the dynamic environment.

Sensitivity of Biological Activity to Oscillatory Flow: For the chosen idealized NPZ model, results from the 2D idealized simulation indicated that, in general, lower oscillation frequencies allowed the biology to adjust to new depth levels, resulting in higher biological activity (e.g., a phytoplankton bloom). Biological time scales typically range from 0 to 50 days, and depend strongly on parameters and depth. The physical time scale was either the oscillation period or the time required for a parcel of fluid to advect over the bathymetry. Comparing these time scales leads to the conclusion that little physically-driven biological activity is expected when the physical time scale is much faster than the biological time scale. Biological activity (standard deviations) along different streamlines presented interesting, consistent behavior with oscillation frequency (Figure 9). Several resonant peaks were seen for very low frequencies, followed by one or two wider resonant peaks and then a monotonic decrease for all higher frequencies. The streamline that was closest to the surface (and entirely contained in the euphotic zone) had the smallest magnitudes of biological activity and the streamline that was about 50% in the euphotic zone and 50% in deeper waters had the largest magnitudes. An analytical model to identify the resonant frequencies for the coupled equations (assuming a small perturbation from the equilibrium) identifies only very low frequencies and is depth dependent. This analysis does not look at streamlines or consider bathymetry, so these two parameters are likely the cause of the additional resonant peaks seen in the biological activity and physical frequency study.

I**MPACT/APPLICATIONS**

This research will contribute to coastal physical and biogeochemical oceanography in general and dynamics of Straits in particular. This will increase capabilities of navy operations in these regions,

especially the surveillance of transit routes, safety of man-based activities, management of autonomous vehicles, and overall tactical and strategic decision making under uncertainties in sensitive areas.

TRANSITIONS

Interactions and coordination are ongoing with several investigators and teams involved with this DRI, specifically with observational efforts, and numerical and theoretical modeling investigations. Our model forecasts and re-analyses netcdf files were made available to the whole team. Monthly climatologies, remapped using our FMM-based scheme, were generated on the ROMS grid and transitioned to H. Arango (Rutgers) for his OBCs. Our codes to implement OBCs similar to those of Perkins et al. nesting boundary conditions were also transferred to H. Arango (Rutgers).

RELATED PROJECTS

Collaborations occur under the ONR grant "Physical and Interdisciplinary Regional Ocean Dynamics and Modeling Systems" (N00014-08-1-1097).

PUBLICATIONS

Agarwal, A., 2009. Statistical Field Estimation and Scale Estimation for Complex Coastal Regions and Archipelagos. SM Thesis, Massachusetts Institute of Technology, Department of Mechanical Engineering, May 2009. [Published]

Burton, L.J., 2009. Modeling Coupled Physics and Biology in Ocean Straits with Application to the San Bernardino Strait in the Philippine Archipelago. SM Thesis, Massachusetts Institute of Technology, Department of Mechanical Engineering, May 2009. [Published]

Logutov, O.G., 2008. A multigrid methodology for assimilation of measurements into regional tidal models, Ocean Dynamics, 58, 441-460, doi:10.1007/s10236-008-0163-4 [Published, refereed]

Logutov, O.G. and P.F.J. Lermusiaux, 2008. Inverse Barotropic Tidal Estimation for Regional Ocean Applications, Ocean Modelling, 25, 17-34. doi:10.1016/j.ocemod.2008.06.004 [Published, refereed]

Ueckermann, M. P., 2009. Towards Next Generation Ocean Models: Novel Discontinuous Galerkin Schemes for 2D unsteady biogeochemical models. SM Thesis, Massachusetts Institute of Technology, Department of Mechanical Engineering, Sept. 2009. [Published]

Presentations and publications are available from the MSEAS web-site. Specific figures are available upon request.
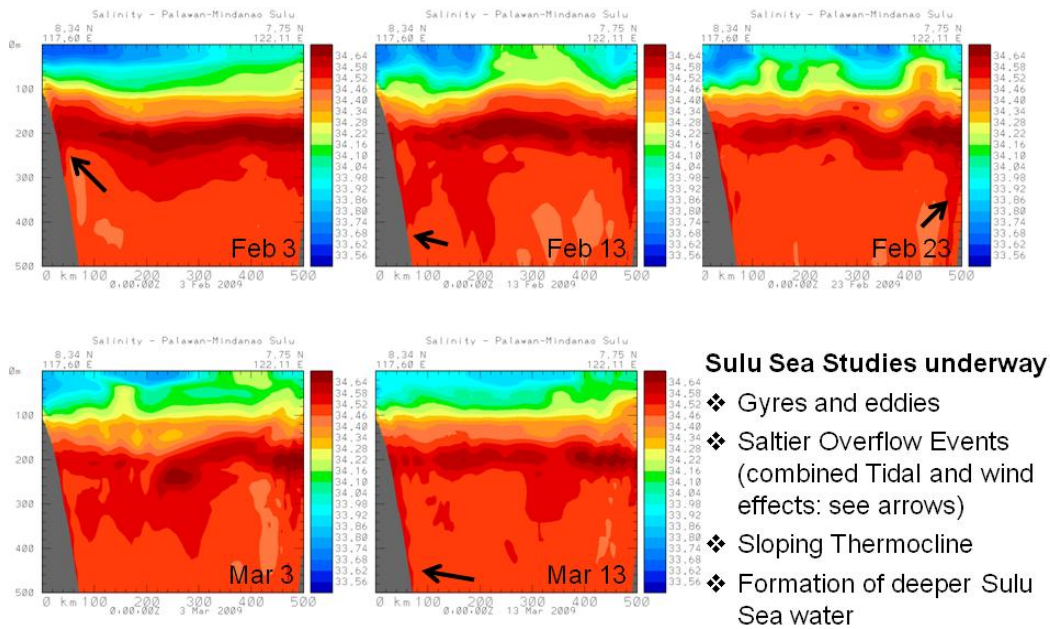
Figure 1. Impact of Sulu Sea gyres on overflow effects and formation
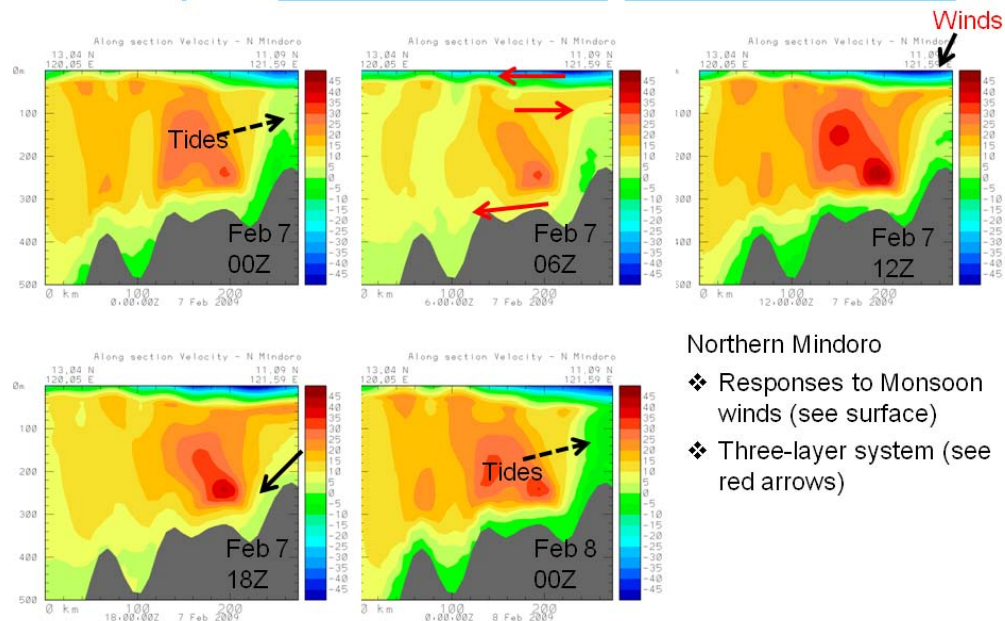
Figure 2. Mindoro Strait response to winds and tides
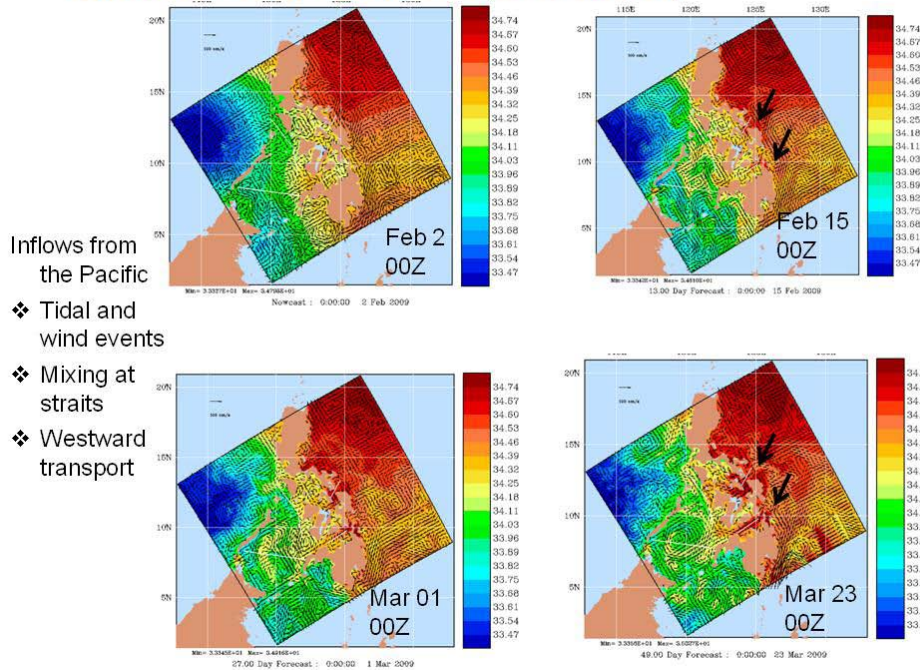
Figure 3. Salinity inflows into Philippine archipelago
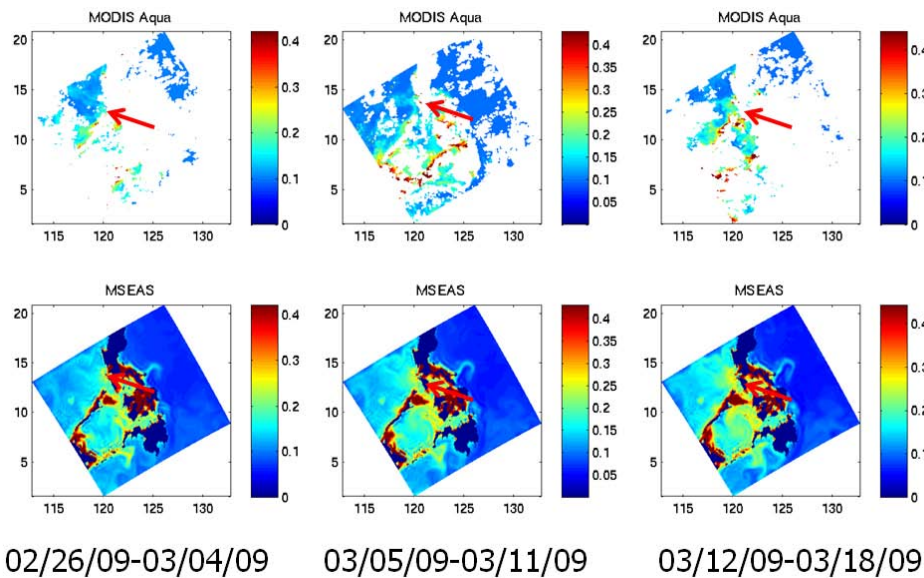
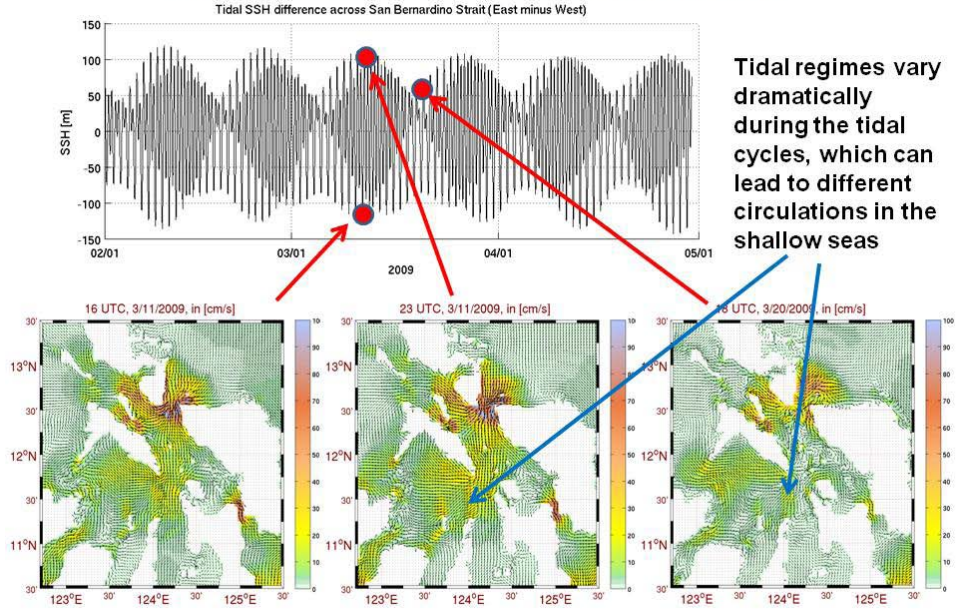Figure 4. Comparison of MSEAS chlorophyll estimates with satellite imagery

Figure 5. Inverse tidal modeling – illustrating spatially inhomogeneous nature of tidal flow fields
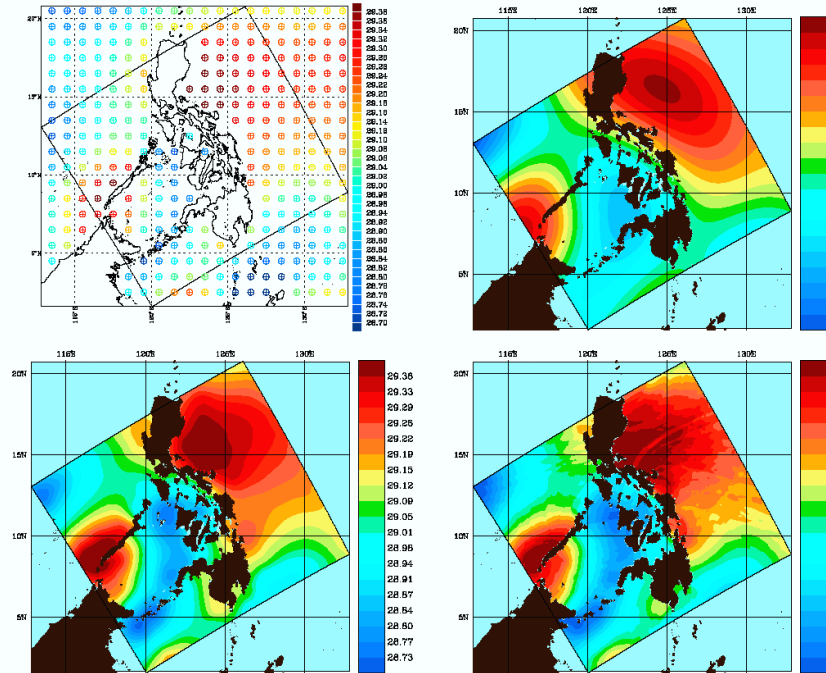
Figure 6: (Top - Left) World Ocean Atlas 2005 Climatology in situ temperature (^{o}C) at 0m; Temperature (^{o}C) OA Fields obtained using: (Top - Right) Standard OA without taking islands into account; (Bottom - Left) Fast Marching Method; (Bottom - Right) SPDE approach (representing field by a stochastically forced Helmholtz Equation).
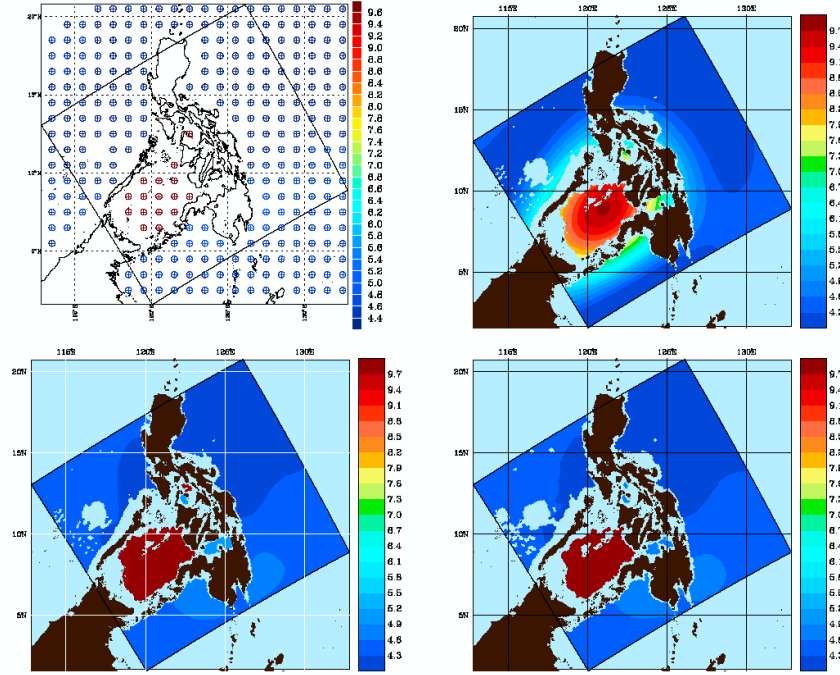
Figure 7: (Top - Left) World Ocean Atlas 2005 Climatology in situ temperature (^{o}C) at 1000m; Temperature (^{o}C) OA Fields obtained using: (Top - Right) Standard OA without taking islands into account; (Bottom - Left) Fast Marching Method; (Bottom - Right) SPDE approach (representing field by a stochastically forced Helmholtz Equation).
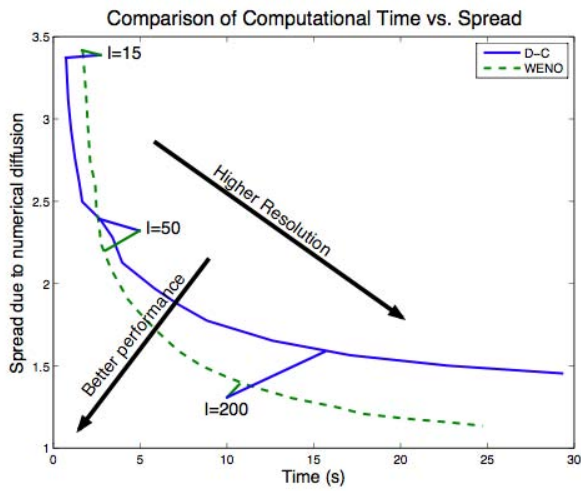

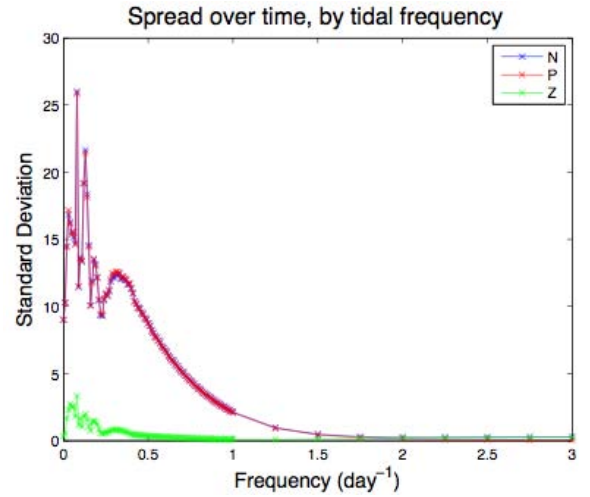Fig. 8: Comparison of Donor-Cell and WENO scheme results.

Fig. 9: Sensitivity of biological activity to oscillatory flow